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Benchmarking Sustainability Practices Use throughout Industrial Construction Project Delivery

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Academic Editor: Marc A. Rosen
Received: 7 April 2017; Accepted: 7 June 2017; Published: 10 June 2017

Abstract: Despite the efforts for sustainability studies in building and infrastructure construction, the sustainability issues in industrial construction remain understudied. Further, few studies evaluate sustainability and benchmark sustainability issues in industrial construction from a management perspective. This study presents a phase-based benchmarking framework for evaluating sustainability practices use focusing on industrial facilities project. Based on the framework, this study quantifies and assesses sustainability practices use, and further sorts the results by project phase and major project characteristics, including project type, project nature, and project delivery method. The results show that sustainability practices were implemented higher in the construction and startup phases relative to other phases, with a very broad range. An assessment by project type and project nature showed significant differences in sustainability practices use, but no significant difference in practices use by project delivery method. This study contributes to providing a benchmarking method for sustainability practices in industrial facilities projects at the project phase level. This study also discusses and provides an application of phase-based benchmarking for sustainability in industrial construction.

Keywords: sustainability; benchmarking; industrial construction; project nature; project delivery methods

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1. Introduction

Construction is a major industry in the global economy. In 2015, the global construction market reached US$9.5 trillion, accounting for more than 10% of global gross domestic product (GDP) [1]. Within the global construction market, industrial construction accounts for 21% [1], but sustainability studies have usually focused on the other two sectors, building and infrastructure. However, industrial construction is usually the most complex sector, and involves more dangerous facilities. Consequently, if sustainability issues, such as environmental or safety accidents, occur in an industrial project, the impact is more severe than for building and infrastructure projects. For example, British Petroleum (BP) spent US$56.4 billion in court fees, penalties, and cleanup costs for its Mexican gulf oil spill [2]. Therefore, industrial construction projects require sustainability management practices to minimize negative environmental impacts throughout the project delivery process for industrial facilities.

To continuously improve performance, benchmarking is typically used as a strategic tool for managing industrial facilities project delivery [3,4]. In recent decades, benchmarking has enabled construction firms to create the competitiveness necessary to improve organizational performance [3–14]. Most benchmarking approaches use lagging indicators, which typically measure performance outcomes after project completion, to assess cost, schedule, changes, safety, and productivity, the traditional goals of project management. However, the existing benchmarking studies of construction projects [15–17] have recently paid attention to sustainability issues of a construction project, focusing on environmental sustainability. Efforts to develop effective sustainability measures to evaluate the organizational capability and performance required to meet green requirements in the construction industry, such as requirements for energy efficiency, renewable energy use, and CO_2 emission, are recent [15,17,18]. Furthermore, existing sustainability studies in project benchmarking focus more on developing indicators for environmental sustainability for building or infrastructure projects than for industrial facilities projects [7,19].

Further, few studies focus on benchmarking for sustainability in the earlier project phases, such as front-end planning, engineering, and procurement. Most studies focus on the construction phase rather than other project phases or the entire project delivery process. Therefore, the construction industry needs a more flexible and dynamic benchmarking approach for sustainability, which measures and compares management capability of project organization using leading indicators during an on-going construction project [3,4].

To address these issues, the Construction Industry Institute (CII) developed the "10-10 Program", a phase-based benchmarking program that evaluates processes, practices, and organizations in construction project delivery [3,4]. The "phase-based" benchmarking evaluates organizational capability, performance, and practices at the project-phase level to compare them with each project phase for similar construction projects delivery [3,4]. In the benchmarking program, sustainability is a significant project management input that project organizations must pay attention to when managing the entire project life cycle. CII defines sustainability practice as project management practices that could affect project processes and performance outcomes environmentally, economically, or socially [20]. For instance, in an industrial facilities project, environmental regulatory requirements will belong to environmental sustainability as well as social sustainability in all project phases, from front-end planning to startup.

This paper aims to present a phase-based sustainability benchmarking framework and measurement, which evaluates sustainability practices use at the project-phase level throughout industrial construction project. To achieve this purpose, this study takes four steps, as shown Figure 1. First, this study reviews the research gaps between previous benchmarking and sustainability studies. This study focused on a gap between project performance indicators, a gap between lagging and leading indicators and a gap between construction sectors. Second, this study develops a phase-based sustainability benchmarking framework and measurement throughout five sequences: (1) developing benchmarking framework; (2) identifying sustainability practices; (3) developing survey instrument; (4) quantifying sustainability practices use; and (5) collecting project data. Third, this study assesses the level of sustainability practices use in industrial facilities projects across the project phase. This assessment is analyzed into two parts. First part is analyzed without considering specific groups such as project type, nature and delivery methods. Second part is analyzed with considering these specific groups. Finally, this study discusses the applications of the sustainability measure in benchmarking of industrial facilities projects, summaries the findings of assessment, suggests limitation and future studies.

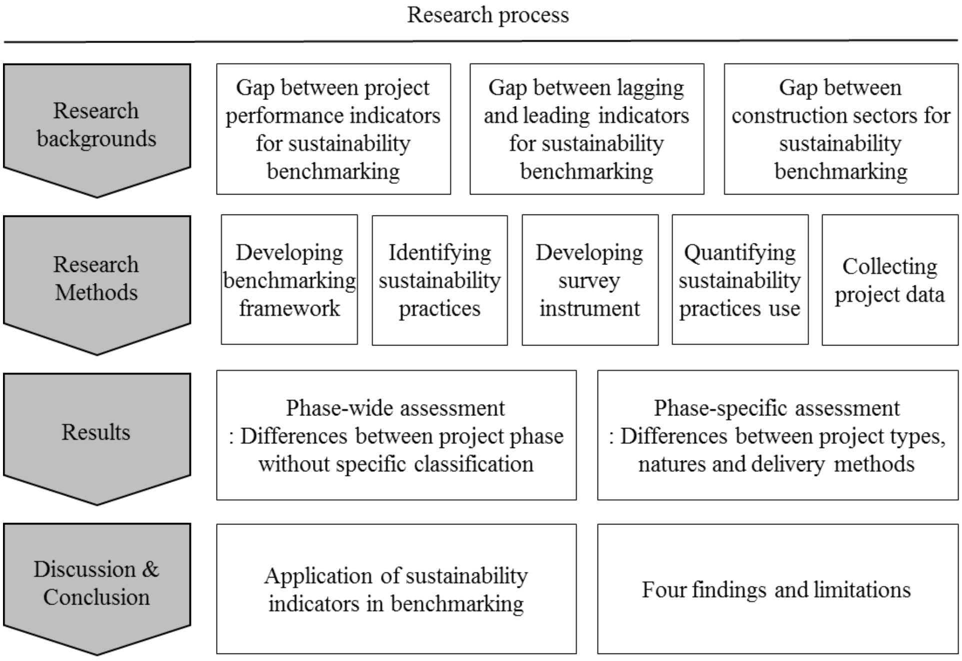

Figure 1. Research process.

2. Research Background

2.1. Project Benchmarking in Construction

Project benchmarking in construction is a process of continuous improvement based on comparing an organization's process or products with best practices [21]. Over the past two decades, project benchmarking evolved into a strategic process to continuously improve performance outcomes for construction projects [22]. Many researchers have suggested effective measures to evaluate project performance [5–7,11,13,23,24]. The research focus is primarily on a performance index of cost, schedule, and quality as these are the traditional success factors in construction projects [5,7,22,25–28]; however, safety performance is also included [7,9,13,19,29,30]. Several researchers dealt with customer satisfaction [7,9,30,31] and change management [9,19,29]. However, few researchers provided sustainability metrics from a benchmarking standpoint. Rankin et al. (2008) suggested sustainability metrics for design and construction phases, which are measures for the improved level of sustainability as measured against a checklist of standard practices in terms of site, water usage, energy usage, materials and indoor environment [19]. Castro et al. (2015) developed sustainability benchmarks for resources consumption, waste production, operating costs, and potential environmental impact related to the operational phase of healthcare buildings [32]. Thus, this study attempts to focus on developing sustainability benchmarking frameworks to overcome the research gaps discussed in Sections 2.2 and 2.3.

2.2. Lagging and Leading Indicator of Constrution Sustainability

Over the past decades, sustainability indicators underwent a significant advance [15,33]. Since the existing benchmarking methods adopted ex-post evaluation, most sustainability indicators utilized ex-post lagging indicators that track construction project performance outcomes after project completion. From this management perspective, Keeble et al. (2003) identified 69 indicators and grouped them into 37 sub-criteria under 15 criteria for economic, social, environmental quality, and use of natural resources [34]. Rankin et al. (2008) suggested sustainability metrics for design and construction phases, which are measures of the improved level of sustainability measured against a checklist of standard practices for site, water usage, energy usage, materials, and indoor environment [19]. Ugwu and Haupt (2007) identified 30 key performance indicators for infrastructure sustainability for economy, environment, society, resource utilization, health and safety, and project management/administration [35]. Fernández-Sánchez and Rodríguez-López (2010) identified 41 sustainability indicators and classified them into the three sustainability domains as a sustainable breakdown structure [36]. Social sustainability indicators were categorized into six subcategories: culture, accessibility, participation, security, public utility, and social integration. Environmental sustainability indicators were grouped into six subcategories: soil, water, atmosphere, biodiversity, resources, and energy. Economic sustainability indicators were classified into five subcategories: costs, technical requirements, bureaucracy, social economy, and heritage. Yeung et al. (2013) selected environment performance as one of the lagging indicators to develop a composite performance indicators [7]. Heravi et al. (2015) identified 42 sustainability indicators for industrial building focused on petrochemical projects: (1) 18 environmental indicators, such as climate change, air pollution, noise pollution, public health and safety, renewable raw material; (2) 7 social indicators, such as employment, public comport, cultural heritage; and (3) 17 economic indicators, such as effects on national economic indicators, use of national resources, use of regal resources [15].

However, to manage sustainability efficiently, construction projects need more proactive sustainability indicators that measure and compare sustainability capability and project organization performance against leading indicators while projects are ongoing, and afterward [3,4]. In addition, the increase in uncertainty within the global construction market means a more proactive evaluation is warranted to respond to rapid changes in the construction business environment. This study aims to develop leading indicators for proactive sustainable project management.

2.3. Sustainability for Industrial Construction

An industrial facility encompasses a physical plant, building, and machinery, or more commonly, a complex with several physical plants or buildings to manufacture various products from raw materials. A large amount of energy is used during operation, and significant amounts of waste are generated, which can be harmful and dangerous. Despite the importance of sustainability issues, few research efforts address sustainability in industrial construction [15–18]. Cuadrado et al. (2012) and San-Jose Lombera and Garrucho Aprea (2010) suggest sustainability indicators based on the three fundamental dimensions of sustainability: environmental, social, and economic [16,17]. In addition, these sustainability considerations require a considerable amount of additional capital to build and maintain a more sustainable industrial facility. Therefore, Cuadrado et al. (2012) suggest that economic indicators for sustainable industrial construction for regional economic development, such as regional growth and competition enhancement in market, in the area the industrial facility is built [17].

However, these studies only focused on construction and operation phase. They did not also consider industrial project characteristics such as project type, project nature and project delivery method even though there are some causalities for sustainability benchmark to differ according to project characteristics. Thus, this study investigated the level of sustainability considering project phase, project type, project nature and project delivery method. These project type categorizations are derived from CII's classification. The CII's categorize industrial facilities into two groups, heavy and light. Heavy industrial facilities involve large and heavy equipment, and facilities reaching a certain level of environmental impact, such as chemical manufacturing, electrical (generating), environmental, mining trailing, natural gas processing, oil/gas exploration/production (well-site), oil refining, oil sands mining/extraction, oil sands SAGD, oil sands upgrading, and cogeneration [37–39]. Light industrial facilities involve manufacturing or production of relatively smaller consumer goods, with less environmental impact than those associated with heavy industrial facilities, such as pulp and paper, automotive manufacturing, consumer products manufacturing, foods, microelectronics manufacturing, office products manufacturing, pharmaceutical manufacturing, pharmaceutical labs, and clean room (hi-tech) [37–39].

3. Research Methods

3.1. Developing Benchmarking Framework

This study developed a conceptual framework for evaluating sustainability practices use throughout project delivery process for industrial facilities. The research team adopted a "phase-based" approach that measures the level of implementation of sustainability practices in each project phase at the end of project phases for industrial facilities construction. This study defines this framework as "phase-based benchmarking framework", which provides how benchmarking for sustainability works in each project phase throughout project delivery process as shown in Figure 2. The framework comprises five project phases: front-end planning, engineering, procurement, construction, and startup, which are the main project phases for an industrial construction project [3].

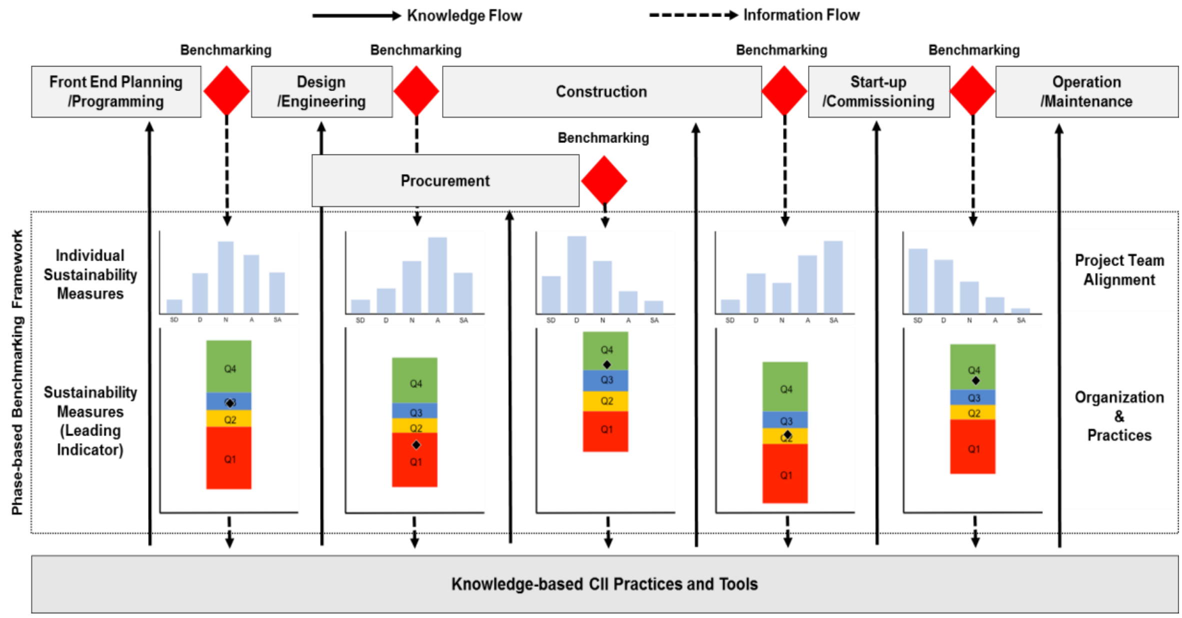

Figure 2. Phase-based benchmarking framework for sustainability practices use.

As shown in Figure 2, the phase-based benchmarking is conducted through two steps at each project phase level. In the first step, project team members evaluate the implementation level of individual sustainability practices at the end of each project phase, and reveal the distribution of individual responses from the project team members showing how the team members are aligned during the project phase. In the second step, the individual measures are combined into one sustainability leading indicator, which presents the level of implementation of sustainability practices use in the project phase. The sustainability indicator represents the level of sustainability practices use of project organization. The benchmarking practitioners compare the quantified level of implementation for a project organization's sustainability practices to similar industrial construction projects in CII's benchmarking database (information flow). Based on the results of this phase-level benchmarking, the industry practitioners figure out their project's level of sustainability practices implementation in each project phase. Furthermore, practitioners uncover proactive strategies to improve sustainability practices use in subsequent project phases or future projects utilizing the knowledge-based CII practices and tools the CII and its members developed from academia and industry over the last three decades (knowledge flow).

The framework enables both phase-focused and phase-wide assessments to maximize the benefits of benchmarking for sustainability integrating performance measurement in each project phase with progress measurement across project phases. The phase-focused assessment can evaluate and compare sustainability practices use with other industrial facilities projects or industry norms within a specific phase: while the phase-wide assessment is a cross-phase evaluation to track and compare sustainability practices use with those in preceding or subsequent phases. The phase-focused assessment as a performance measurement evaluates the extent to which the project organization implements sustainability practices in each project phase. However, the phase-wide assessment as progress measurement evaluates the extent to which the project organization implements the sustainability practices as the project progresses. Based on the conceptual framework, the research team determined sustainability practices for industrial facilities projects and quantified their level of implementation.

3.2. Identifying Sustainability Practices

Based on the conceptual benchmarking framework, this study identified sustainability practices to develop a sustainability leading indicator for construction projects. In so doing, the research team reviewed management practices that could be related to sustainability in construction projects. The review process included an evaluation of CII resources, such as previous CII benchmarking questionnaires, implementation resources, and research reports [20,37,38,40–47]. In addition, academic resources dealing with sustainability indicators and practices were reviewed [15–17,35,36,48–52]. Furthermore, the research team reviewed publications that industry practitioners created, such as McGraw Hill's Smart Report [53,54] and consulting companies, such as PriceWaterHouseCoopers (PwC) and Independent Project Analysis [4,55].

Based on the literature review, the research team and industry experts, who were involved in CII activities and events held in 2012 and 2013, evaluated and discussed all possible indicators representing project management practices. The industry experts are CII's board members, members of the CII Performance Assessment Committee and Community of Practices, and senior executives and managers representing their organizations and oversee CII and contribute to CII activities and events. Further, on average, the industry experts had over 20 years of industry experience as project managers and benchmarking professionals with expertise in construction projects in various industry sectors. At the April 2013 CII board meeting, more than 60 board members discussed and tried to articulate the significant leading indicators, including sustainability, that support capital project delivery. Based on the review of existing sustainability practices and from the discussion among industry experts, the research team confirmed seven management practices related to sustainability throughout construction project delivery, from front-end planning to startup.

The sustainability practices identified are: (1) prefabrication, preassembly, modularization, and offsite construction (PPMOF) evaluation [20,43–45,48,49,52,54,56,57]; (2) startup processes and systems [20,42,46,47]; (3) meeting startup quality [20,42,46,47]; (4) community relations [15,20,58–62]; (5) life cycle cost analysis [20,32,36,48,50,57,61,63]; (6) regulatory requirement, permitting, and environment [15,20,35,60,61,64–66]; and (7) sustainability [20,35,64,66]. The description and sources of sustainability practices from the literature review are summarized in Table 1.

For instance, a PPMOF evaluation investigates the appropriateness of applying PPMOF practices to the facility to be built. The PPMOF has multiple sustainable impacts for construction: (1) improve productivity and reduce cost (economic); (2) improve workers' safety at the construction site (social); and (3) control and reduce environmental impacts (environmental) [20,43–45,48,49,52,54,56,57]. Therefore, the evaluation of the PPMOF practice is usually implemented in the front-end planning phase, and associated with all three sustainability dimensions: environmental, social, and economic.

Then, the research team and the members of the CII Performance Assessment Committee and Practice of Communities discussed and selected the sustainability practices in each sustainability area and project phase where the practices are most implemented throughout the project delivery process. Based on this process, each sustainability practice was allocated to a relevant sustainability area and project phase based on its attributes, as summarized in Table 2.

Table 1. Summary of sustainability practices for industrial construction.

Practice	Description	Sources
PPMOF evaluation	The evaluation and determination of prefabrication, preassembly, modularization, and offsite construction in front-end planning phase to achieve specific strategic objectives and improved project outcomes. Includes developing a business case and execution strategy for large-scale transfer of stick-built construction effort from the jobsite to fabrication shops or yards. The PPMOF enables improved productivity, reduced cost, improved workers' safety at the construction site, and control and reduction of environment impacts.	Tatum et al. (1987), Fisher and Skibniewski (1992), Hass and Fagerlund (2002), Hass and Song (2002), Yates (2008), McGraw Hill Construction (2011), Nahmmens and Ikuma (2012), Ahn and Kim (2014), Kamali and Hewage (2016), Kamali and Hewage (2017)
Startup processes and systems	Startup is the transitional phase between construction completion and commercial operation of an industrial facilities project, including all activities that bridge these two phases. The startup processes and systems are formalized processes to conduct effective startup activities, including objective setting, startup execution plan, and communication and safety management.	CII (1990), O'Connor et al. (1999), Yates (2008), O'Connor et al. (2016).
Meeting startup quality	Startup quality is managed and controlled in startup quality gates, which is a mechanism to check the startup execution plan, organization, and management system for operation and maintenance, commissioning, and permitting, environmental compliance, etc.	CII (1990), O'Connor et al. (1999), Yates (2008), O'Connor et al. (2016).
Community relation issues	Community relations are social issues related to sustainability such as sweat equity to local organizations, minority owned business outreach, social impact of noise, traffic, safety, and aesthetics, community development, use of local labor, economic impact on local business and communities, actively managing community relations, providing days off for cultural holidays, interaction with the public, public health impacts, elimination of high traffic conditions, and impact of the workforce on the local economy.	Cohen-Rosenthal (2000), Louw and Bontekoning (2007), Yates (2008), Chong et al. (2009), Ortiz et al. (2009), Chen et al. (2010), Heravi et al. (2015), Onat et al. (2017).

Table 1. *Cont.*

Practice	Description	Sources
Life cycle cost analysis and considerations	Life cycle cost analysis is an economic assessment of material, location, system, or facility that considers all significant costs of ownership over its economic life. The life cycle cost includes initial cost, maintenance costs, operating costs, replacement or refurbishment cost, retirement cost, disposal cost, and other costs, such as taxes, depreciation, and additional management cost. It also evaluates how construction materials are transported to and from facilities and assesses the disposition of materials from the moment the raw materials are purchased through their salvage as construction wastes.	Shen et al. (2007), Yates (2008), Khasreen et al. (2009), Ortiz et al. (2009), Fernández-Sánchez and Rodríguez-López (2010), Castro et al. (2015), Günkaya et al. (2016), Kamali and Hewage (2016), Kamali and Hewage (2017), Onat et al. (2017).
Regulatory requirements, permitting, and environmental issues	Regulatory requirements are government regulations and global standards for environmental sustainability that engineering and construction professionals comply with. There are various environment requirements and compliance issues, like the United Nations Framework Convention on Climate Change, Kyoto Protocol Treaty, Basel Convention, Rio Declaration, Stockholm Convention, Global Environment Management Standards (ISO 14000), United States Environmental Protection Agency (EPA) Laws.	Ugwu and Haupt (2007), Yates (2008), Alwaer et al. (2008), Ali and Al Nsairat (2009), Chong et al. (2009), Ortiz et al. (2009), Heravi et al. (2015), Onat et al. (2017)
Sustainability considerations	Various sustainability considerations are included during constructability review, design, and construction phases, including energy efficiency, environmental impacts, social and community impacts, social responsibility, resources efficiency, renewable energy, sustainable design, producing less waste and recycling more waste, and reducing noise and spatial pollution.	Ugwu and Haupt (2007), Yates (2008), Alwaer et al. (2008), Onat et al. (2017)

Table 2. Classification of sustainability practices by sustainability area and project phase.

Sustainability Practices	Sustainability Area			Project Phase				
	ENV	SOC	ECO	FEP	ENG	PRO	CON	STA
PPMOF evaluation	√	√	√	√				
Startup processes and systems	√							√
Meeting startup quality	√		√					√
Community relation issues	√	√		√	√		√	√
Life cycle cost analysis and considerations	√		√	√	√	√		
Regulatory requirement, permitting, and environmental Issues	√	√		√	√	√	√	√
Sustainability consideration	√	√	√			√	√	√

Note: ENV (Environmental), SOC (Social), ECO (Economic), FEP (Front-End Planning), ENG (Engineering), PRO (Procurement), CON (Construction), and STA (Startup).

3.3. Developing Survey Instruments

To measure the implementation level for the selected sustainability practices, this study adopted a questionnaire survey to collect project data of industrial construction projects. Since the survey is an effective method when large amounts of data need to be collected at one time [23,51], and the sustainability practices are usually measured by a statement-based measurement [3,4].

This study's survey instrument incorporates questions of sustainability practices use derived from the literature review and inputs from industry experts. To evaluate sustainability practices, use throughout the project delivery process, five different phase-specific questionnaires with a different number of questions asked were used to customize questionnaires for an industrial facilities project and its five main project phases. The research team used the questionnaire in each project phase to evaluate sustainability practices use by project phase. The questions for the survey instrument adopted a statement-based assessment with five-point Likert scale, ranging from strongly agree to strongly disagree. Statement-based assessments must avoid possible measurement bias from the potential inconsistency in responses due to respondents' subjective perceptions [25,67–69].

To minimize potential measurement bias because of subjective assessment, this study designed the questionnaires to evaluate sustainability practices use based on multiple responses collected from diverse project team members and project stakeholders directly involved in an industrial facilities project. This approach reduces the latent effects of measurement biases, and avoids misleading the meaning of the results representing the industry benchmark because mean value of the responses from multiple team members could represent the average level of implementation of the sustainability practices [67,68]. This approach provides an additional benefit of aligning project team members and stakeholders participating in each project phase.

3.4. Quantifying Sustainability Practices Use as Leading Indicator

This study established a quantification procedure for sustainability practices use by incorporating individual sustainability indicators for equivalent comparisons with other projects. The sustainability practices use is quantified in three steps: (1) calculating scores of individual questions of each sustainability indicator; (2) weighting individual sustainability indicators; and (3) aggregating and standardizing the sustainability score. The normalized score ranges from 0 to 100, indicating the level of sustainability practices use.

Industry experts actively involved in the CII's activities determined the weight of each question. They evaluated each question in the sustainability indicator with the three-point Likert scale: high (3); medium (2); and low (1). Based on the experts' assessments, the average weighted score for the sustainability indicator was calculated, and then normalized. Finally, the weights were used to calculate the weighted individual question score by multiplying the score and weight. The weighted scores were aggregated to produce a single value.

3.5. Collecting Project Data

The data from industrial construction projects for this study were extracted from the CII 10-10 Program database. CII collected data through the 10-10 Program System, an online phase-based performance assessment system. The online questionnaire was open to both CII member organizations, including owners, contractors, and suppliers in the global construction industry. As of 2016, 816 responses from 524 phase-based data of industrial facilities projects have been collected from 70 companies. Account managers responsible for investigating ambiguous data points and validating the submitted data in the CII Performance Assessment Team conducted a course of data validation to verify and cleanup the collected data. Table 3 summarizes the distribution of the project data collected into CII's database by project type, project nature, and project delivery method.

Table 3. Summary of industrial facilities project database.

Project Characteristics	Project Phase					
	FEP	**ENG**	**PRO**	**CON**	**STA**	**Sum**
All Industrial	137	125	112	107	43	524
Project Type						
Heavy Industrial	122	110	107	95	40	474
Chemical Manufacturing	39	37	24	25	9	134
Electrical (Generating)	11	12	13	16	9	61
Natural Gas Processing	18	16	18	12	6	70
Oil Refining	21	18	17	9	3	68
Oil/Gas Exploration/Production	18	14	21	16	10	79
Other Heavy Industrial	15	13	14	17	3	62
Light Industrial	15	15	5	12	3	50
Project Nature						
Addition	38	36	35	33	16	158
Brownfield	16	18	10	15	3	62
Grass Roots	32	32	40	27	16	147
Modernization	51	39	27	32	8	157
Project Delivery Methods						
Design-Bid-Build	72	80	50	47	21	270
Design-Build (EPC)	57	40	56	53	19	225
CM at Risk	6	4	3	6	3	22

Note: FEP (Front-End Planning), ENG (Engineering), PRO (Procurement), CON (Construction), STA (Startup).

Most of the project data collected came from heavy industrial facilities projects, which limits the analysis by industry group. Thus, more analyses will be possible when more data are collected from light industrial facilities projects. Among the types of heavy industrial facilities projects, the largest types collected from phase-based project data were from five project types: chemical manufacturing, electrical, natural gas processing, oil refining, and oil/gas exploration/production. The distribution by project types shows that chemical manufacturing comprises most of the collected project data among project types.

The distribution of collected data by project nature demonstrates that addition has the largest number of data points for project nature, and the data for other project nature, except brown field projects, are relatively equally distributed. However, the distribution by project delivery method, which is an approach used to organize a project team to manage the delivery of a project, shows that design-bid-build method, including parallel prime contract method and design-build or EPC (Engineering-Procurement-Construction) method, comprise the largest amount of data in the database.

Looking at the distribution of collected data, the front-end planning phase has the largest number of data points by project phase, and the data for the four project phases, except startup, are relatively equally distributed.

4. Assessment of Sustainability Benchmarks

4.1. Phase-Wide Assessment

This study evaluates the level of sustainability practices use in industrial facilities projects across the project phase. Analysis of Variance (ANOVA) and Tukey's honest significant difference (HSD) tests were conducted using IBM SPSS software to assess the level of sustainability practices use. First, ANOVA was conducted to assess if the means of sustainability practices use is different among project phases. Then, post hoc comparisons were conducted using Tukey's HSD test to determine which pair of project phases is significantly different among combinations. The post hoc comparison is frequently used in conjunction with ANOVA to identify which pairs of groups show statistically significant mean differences [70]. Tukey's HSD test is a single-step multiple comparison procedure and statistical test performed in conjunction with ANOVA (post-hoc analysis) to detect a pairwise comparison with means that are significantly different from each other at a 0.05 significance level [30]. Prior to the analysis, the dataset of input measure scores was refined by removing outliers. Then, three basic assumptions were checked and verified: independence, normality, and homogeneity of the variance of the residuals.

Table 4 lists out the descriptive statistics and ANOVA results of sustainability benchmarks by project phase. The mean values represent the level of sustainability practices use, and the standard deviation (SD) values show the variances of their distribution. ANOVA test result showed sustainability scores were significantly different between project phases at a 0.05 significance level (F = 19.158; p = 0.000). Sustainability scores in construction and startup phases were higher than those in pre-construction phases in industrial facilities projects. Among the pre-construction phases, the sustainability score is higher for the front-end planning phase than engineering or procurement phases. In addition, standard deviation indicates that the variance in distribution of sustainability practices across the project phase ranges from 15.97 to 26.10, which means that project organizations of industrial facilities projects implemented sustainability practices within a broad range from a very low level to a very high level. This implies that sustainability practices have yet to be fully defined in construction project delivery, so it varies widely among project organizations.

Table 4. Descriptive statistics and ANOVA results of sustainability benchmarks by project phase.

Project Phase	Mean	SD	F	Sig.
Front-End Planning	56.34	24.75	19.158	0.000
Engineering	45.81	22.22		
Procurement	48.99	26.10		
Construction	68.00	19.30		
Startup	67.93	15.97		

Table 5 summarizes significant results for post hoc comparisons using Tukey's HSD test. For post hoc comparisons, the mean score of sustainability practices use in front-end planning phase was significantly different and higher than the engineering phase, at a 0.05 significant level (p-value = 0.002). In addition, the mean score of sustainability practices use in the construction phase was significantly different and higher than in the front-end planning phase (p-value = 0.001), engineering phase (p-value = 0.000), and procurement phase (p-value = 0.000). The mean score of sustainability practices use in the startup phase was also significantly different and higher than those of the front-end planning phase (p-value = 0.031), engineering phase (p-value = 0.000), and procurement phase (p-value = 0.000).

Table 5. Post hoc comparisons of sustainability benchmarks by project phase.

Project Phase (I)	Project Phase (J)	Mean Diff. (I-J)	S.E.	Sig.
Front-End Planning	Engineering	10.527	2.823	0.002
Construction	Front-End Planning	11.657	2.944	0.001
	Engineering	22.184	3.006	0.000
	Procurement	19.005	3.085	0.000
Startup	Front-End Planning	11.586	3.989	0.031
	Engineering	22.114	4.035	0.000
	Procurement	18.935	4.094	0.000

4.2. Phase-Specific Assessment

4.2.1. Project Type

The study investigates the level of sustainability practices use in each project phase by project type using the ANOVA test. Considering the number of project data by project phase and project type, as summarized in Table 2, this study selected five major project types with more than three data points within a combination set of project phase and project type: chemical manufacturing (N = 134), electrical generating (N = 61), natural gas processing (N = 70), oil refining (N = 68), and oil/gas exploration/production (N = 79).

Table 6 summarizes descriptive statistics and ANOVA results for sustainability benchmarks in each project phase by project type. For the ANOVA test, sustainability scores were significantly different between major project types at a 0.05 significance level in the startup phase (F = 4.110; p = 0.008). However, there was no significant difference among project types in other project phases.

Table 6. Descriptive statistics and ANOVA results of sustainability benchmarks by project type.

Project Phase	Project Type										ANOVA Results	
	Chemical Manufacturing		Electrical Generating		Natural Gas Processing		Oil Refining		Oil Exploration/Production			
	M	S.D.	M	S.D.	M	S.D.	M	S.D.	M	S.D.	F	Sig.
Front-End Planning	52.9	25.0	65.0	19.7	60.2	23.0	59.1	27.1	56.5	29.8	0.631	0.641
Engineering	42.0	20.3	46.5	23.5	54.8	22.8	43.9	21.3	43.4	26.8	0.974	0.425
Procurement	60.8	32.8	36.2	14.4	52.9	26.8	45.1	15.1	48.6	31.7	2.087	0.089
Construction	70.2	21.8	71.1	16.2	59.9	22.1	73.6	13.9	61.3	21.4	1.396	0.243
Startup	70.5	12.6	61.5	8.8	68.6	17.5	97.6	2.3	61.7	19.1	4.110	0.008

The post hoc comparisons using Tukey's HSD test was conducted for the startup phase, as summarized in Table 7. In the startup phase, the mean score of sustainability practices use of oil refining (M = 97.6, SD = 2.3) was significantly different and higher than that of electrical generating (M = 61.5, SD = 8.8) and oil/gas exploration/production (M = 61.7, SD = 19.1) at a 0.05 significant level.

Table 7. Post hoc comparisons of sustainability benchmarks by project type.

Project Phase	Project Nature (I)	Project Nature (J)	Mean Diff. (I-J)	S.E.	Sig.
Startup	Oil Refining	Electrical Generating	36.044	9.668	0.007
		Oil/Gas Exploration/Production	35.897	9.546	0.007

4.2.2. Project Nature

Project nature is a project characteristic that represents whether an industrial facility is newly built, added, or modernized. According to the CII's definition, project nature is classified into four types: grass roots, brown field, addition, and modernization [37,38,40]. If a project is built from the foundation up, and requires the demolition of an existing facility before new construction begins, it is classified as grass roots or green field [39]. When expanding, redeveloping, or reusing property or facilities that may be complicated by the presence or potential presence of a hazardous substance, pollutant, or contaminant, it is classified as brown field or co-locate [39]. A common brown field project is a facility built on abandoned gas stations and dry cleaners, railroad properties, factories, and closed military bases [39]. A new addition, or an add-on, is to tie into an existing facility, often intended to expand a facility's capacity. When a substantial amount of the equipment, structure, or other components is replaced or modified in an existing facility to expand capacity or to improve the process or facility, it is classified as a modernization, renovation, or upgrade [39]. Since the nature of a construction project may affect the level of sustainability practices use, this study also assessed the level of sustainability practices use in each project phase by project nature and investigated its difference using ANOVA test. The distribution of project data by project phase and project nature is summarized in Table 2.

Table 8 summarizes descriptive statistics and ANOVA results of sustainability benchmarks in each project phase by project nature. For the ANOVA results, sustainability scores were significantly different between project nature at a 0.05 significance level in the front-end planning phase (F = 4.440; p = 0.005) and construction phase (F = 5.010; p = 0.003). However, there was no significant difference among project nature and other project phases.

Table 8. Descriptive statistics and ANOVA results of sustainability benchmarks by project nature.

Project Phase	Project Nature								ANOVA Results	
	Grass Roots		Brown Field		Addition		Modernization			
	M	S.D.	M	S.D.	M	S.D.	M	S.D.	F	Sig.
Front-End Planning	55.4	27.5	74.1	18.7	58.7	24.2	49.6	22.5	4.440	0.005
Engineering	47.5	25.3	46.5	19.5	49.4	23.2	40.8	19.6	1.044	0.376
Procurement	51.7	32.0	44.1	17.3	48.4	25.0	47.5	20.6	0.297	0.827
Construction	59.1	18.1	80.1	12.7	65.9	18.6	72.1	20.2	5.010	0.003
Startup	61.5	17.0	76.4	5.1	73.5	14.8	66.4	15.4	1.949	0.138

The post hoc comparisons using Tukey's HSD test were conducted for the startup phase, as summarized in Table 9. In the front-end planning phases, the mean score of sustainability practices use of brown field (M = 74.1, SD = 18.7) was higher than grass roots (M = 55.4, SD = 27.5), addition (M = 58.7, SD = 24.2), and modernization (M = 49.6, SD = 22.5). Brown field and modernization have a different sustainability practice score at a 0.05 significant level. In the construction phase, the brown field (M = 80.1, SD = 12.7) was also higher than grass roots (M = 59.1, SD = 18.1), addition (M = 65.9, SD = 18.6), and modernization (M = 72.1, SD = 20.2). Brown field and grass roots have a different sustainability practice score at a 0.05 significant level.

Table 9. Post hoc comparisons of sustainability benchmarks in each project phase by project nature.

Project Phase	Project Nature (I)	Project Nature (J)	Mean Diff. (I-J)	S.E.	Sig.
Front-End Planning	Brown Field	Grass Roots	18.7	7.305	0.055
		Addition	15.4	7.110	0.139
		Modernization	24.5	6.836	0.003
Construction	Brown Field	Grass Roots	21.0	5.890	0.003
		Addition	14.2	5.696	0.067
		Modernization	8.0	5.724	0.509

4.2.3. Project Delivery Method

The project delivery method is used to organize a project team to manage the delivery of a project. The project submitted into the database is categorized into three project delivery methods: design-bid-build (DBB), design-build (DB), and construction management at risk (CMR) [37,38,71]. DBB is a project delivery method where the agency or owner contracts with separate entities for project design and construction. This method includes parallel prime, a variation of design-bid-build where the owner contracts multiple contractors who perform specific aspects of construction [71]. DB is an integrated delivery process that combines architectural and engineering design services with construction performance under one contract agreement [71]. This category includes engineering-procurement-construction (EPC), which adds procurement services into the DB method. CMR is a delivery method wherein the construction manager acts as agent or consultant to the owner in the development and design phases, but acts as the equivalent of a general contractor during the construction phase [71]. Since the project delivery method may affect sustainability practices use because of the diversity of organizations participating in industrial construction projects, this study also assesses the level of sustainability practices use in each project phase by project delivery method, and investigates its difference using ANOVA test.

Table 10 summarizes descriptive statistics and ANOVA results of sustainability benchmarks in each project phase by project delivery method. For the ANOVA results, there was no significant difference among project delivery methods in each project phase.

Table 10. Descriptive statistics and ANOVA results of sustainability benchmarks by project delivery method.

Project Phase	Project Delivery Method						ANOVA Results	
	DBB		DB		CMR			
	M	S.D.	M	S.D.	M	S.D.	F	Sig.
Front-End Planning	55.0	24.9	57.3	25.3	66.8	18.7	0.678	0.509
Engineering	45.1	22.4	47.3	22.7	51.2	15.9	0.247	0.782
Procurement	47.4	25.0	50.1	28.0	59.4	7.1	0.381	0.684
Construction	66.2	19.9	68.5	19.2	75.8	15.9	0.694	0.502
Startup	66.4	15.9	69.9	17.4	66.3	5.2	0.249	0.781

5. Discussion on Application of Sustainability Benchmarks

Most previous studies of sustainability indicators focused on figuring out which indicators measure critical factors affecting sustainability performance in construction projects [15–17,35,36,48–52]. As aforementioned in research background, a practical application is needed to apply the sustainability indicators as leading indicators assessing the level of sustainability practices use at the project level to establish proactive strategies for subsequent project phases or future projects. Using the industry norms for sustainability practices use calculated by project phase, project nature, and project delivery method, this section discusses applying the sustainability indicator.

The level of sustainability practices use was evaluated using the sustainability indicator developed in this study. The benchmarks measured in each project phase can play the role of early warning indicators in the industrial construction project. Therefore, they also provide proactive management strategies to improve organizational capabilities for dealing with sustainability issues in each phase, for subsequent phases, or future projects. Based on this concept, this paper presents a potential application to utilize the sustainability scores from the perspective of benchmarking as shown in Figure 3.

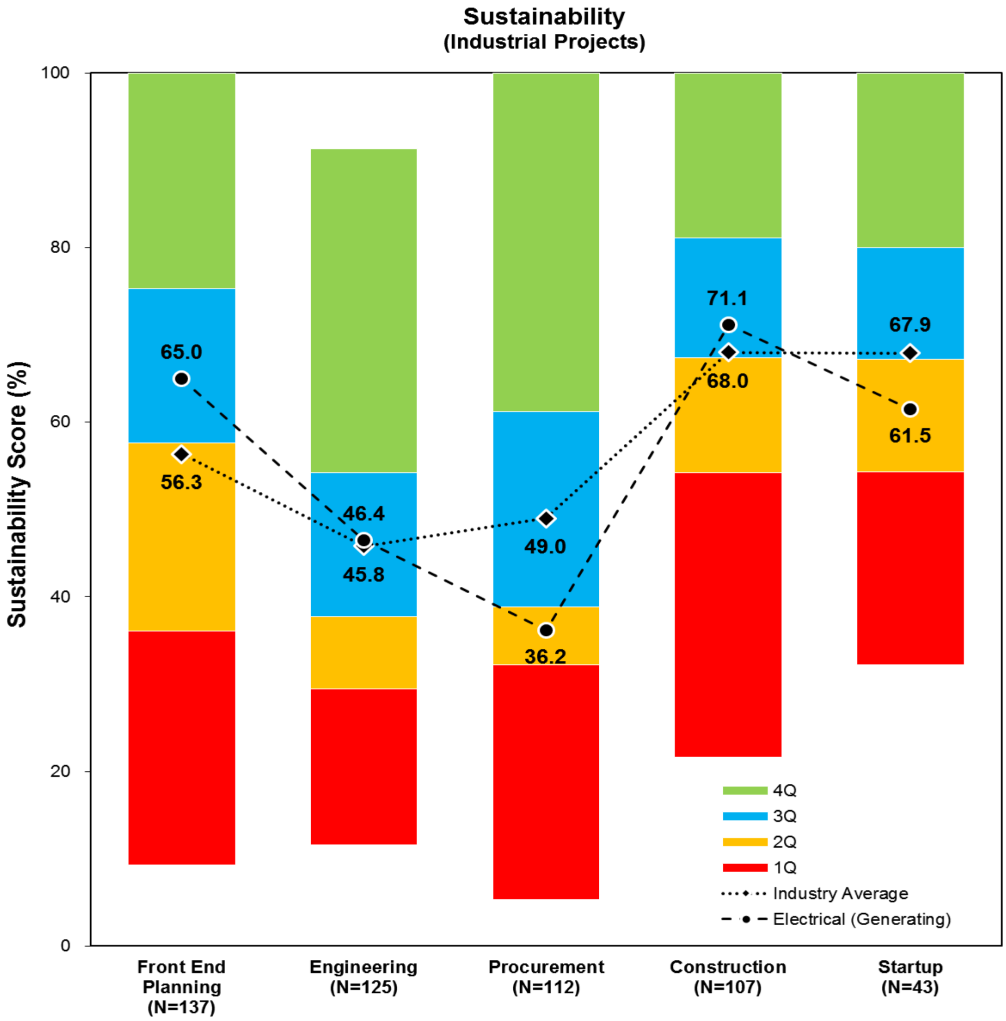

Figure 3. Phase-wide assessment of sustainability practices use in industrial facilities projects.

Figure 3 illustrates the distribution of sustainability indicators for industrial facilities projects in each project phase using quartile ranking that measure of how well the sustainability practices has implemented against all other projects tracked by. The distribution depicts the mean of industrial projects (⧫), the mean of electrical generating projects (●), and four quartiles for sustainability scores, as shown in Figure 2. The first quartile is comprised of the 25% with the best performance, and the fourth quartile is populated with the 25% with the wort performance. The industry practitioners can use this distribution of sustainability scores to compare their project's level of implementation of sustainability practices with the industry norm.

This distribution can also be used for a phase-wide assessment of sustainability practices use across project phase. This phase-wide assessment allows industry practitioners to identify which project phase is vulnerable if implementing sustainability practices, and to determine proactive strategies to improve organizational capabilities in subsequent phases or the same phase in a future project. This assessment can be utilized to provide an early warning indicator forecasting organizational performance in subsequent phases. As shown in Figure 3, the distribution of sustainability scores can be compared to each other by project phase. On average, it indicates that the level of sustainability practices use in industrial facilities projects is relatively lower in engineering (45.8) and the procurement (49.0) phase, and improves in the construction (68.0) and startup (67.9) phase. The mean value for the sustainability score for electrical generating projects is the lowest in the procurement (36.2) phase, while highest in the construction (71.1) phase. The mean value of the sustainability score for electrical generating projects seems like the industry average, but is lowest in the procurement phase. This implies that the sustainability practices in the electrical generating projects are relatively less used than other industrial construction projects. Using these benchmarks, industry practitioners involved in electrical generating projects can evaluate their project's level of implementation of sustainability practices use as a leading indicator and set up management strategies how to improve the implementation of the sustainability practices in subsequent phases or future projects.

6. Conclusions

This paper presents a phase-based benchmarking approach to evaluate sustainability practices use implemented by a project team throughout an industrial construction project. Using 524 phase-level data collected using the framework, this study assessed sustainability practices use by phase-wide and phase-specific assessment. The phase-wide assessment presents the changes in sustainability practices use across the project phase while the phase-specific assessment shows the variation of sustainability practices use by project characteristics, such as project phase, project type, project nature, and project delivery method. Several interesting findings resulted from the assessment.

First, the construction and startup phases, when comparing the five project phases, tend to have a higher implementation of sustainability practices than the other project phases. This finding is unsurprising because previous sustainability studies focused on site construction rather than on earlier phases of capital projects. Second, it is difficult to find a significant difference between project types in most project phases, except the startup phase, when comparing the five major project types. In the startup phase, oil refining tends to have a higher implementation of sustainability practices than electrical generating and oil/gas exploration/production. Since oil refining releases several different chemicals into the atmosphere and expels wastewater into sewage during the refining process, this type of facilities project probably implements sustainability practices more than other types of industrial facilities projects. Third, this study finds that the brown field projects tend to implement sustainability practices more than the others in front-end planning and construction phase when comparing four projects nature because the brown field projects build a facility on the area where another facility was already constructed and demolished. Therefore, sustainability practices need to be implemented more in a brown field project, particularly its front-end planning and construction phases. Finally, this study could not find any significant difference in sustainability practices use among project delivery methods when comparing the three project delivery methods; however, CMR projects tend to implement sustainability practices more than any other delivery method. When more data are collected from CMR projects, the results might show the difference more clearly.

This study's main contribution is the benchmarking framework to assess sustainability practices use with its focus on industrial construction projects. Currently, there are few approaches to the application of sustainability benchmarking to phase-based benchmarking throughout project delivery. With the framework and collected data, this study has provided comparisons to sustainability benchmarks for various project characteristics, such as project type, project nature, and project delivery method. Industry practitioners can use this framework and data to understand the different levels of sustainability practices use for industrial construction by project characteristics. The authors strongly believe that the sustainability benchmarks provided in this study will enable industrial practitioners to establish more practical sustainability strategies for their industrial projects. This study identified and quantified the implementation level for sustainability in industrial construction by incorporating individual sustainability practices use without further investigation of the three major dimensions of sustainability, such as environment, social, and economic. From a management perspective, however, it is debatable whether in practice most management techniques often involve the concurrent use of one or more dimensions of sustainability. For example, the life cycle cost analysis belongs to economic sustainability and environmental sustainability. Therefore, future research could create quantitative measures to evaluate the effects of practices use by the sustainability dimensions. Furthermore, this study should be used as the basis for future study into sustainability benchmarking. For instance, future research could focus on investigating relationships between sustainability practices use and project outcomes, such as cost and schedule performance. Another possible future study could provide specified practical guides to facilitate implementation of sustainability practices in each project phase or each project characteristic to help industry practitioners establish an organization's sustainability strategy efficiently and effectively.

Despite these contributions, this study has specific limitations. Ninety percent of the project's data have been collected from heavy industrial projects. Second, the data points from light industrial facilities projects were insufficient to guarantee reliable results. Therefore, additional data should be collected to evaluate sustainability practices use more reliably in a certain project type in light industrial facilities projects. As more data are collected, it will be possible to evaluate more industrial facilities projects by project type and project phase.

Acknowledgments: This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (No. NRF-2016R1D1A1B03933361).

Author Contributions: Sungmin Yun participated in research conducted by the Construction Industry Institute. He conceived and designed study, analyzed data, and wrote manuscript. Wooyong Jung provided the direction of study, developed overall analysis and revised the manuscripts. All authors have read and approved the final manuscript.

Conflicts of Interest: The authors declare no conflict of interest

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